Low Cost Standalone Display System for Obtaining Real-Time Specific Excess Power Contour Plots In-Flight

Isaac Atuahene†, Rapinder Sawhney††
Industrial and Systems Engineering Department
University of Tennessee
Knoxville, TN, USA
†iatuahen@utk.edu, ††sawhney@utk.edu

Philip Appiah-Kubi*, Rolando Jose Acosta Amando**
*Industrial Engineering Department
Ohio University, Athens, OH, USA
Pa809911@ohio.edu
**Universidad Pantifica Bolivariana, Bucaramanga, Columbia. rolando.acosta@upb.edu.co

Abstract - *A real-time specific excess power (P_s) display is developed and evaluated, and the usability of the display in obtaining direct real-time P_s contours in-flight from level flight acceleration flight test is experimented. Flight simulations were conducted with the UTSI Aviation Systems aircraft on actual flight as well as research flight simulator to validate the display. The algorithm is implemented in the display system using the relation that exists between specific excess power, velocity, flight parameters and forces in flight. Flight test evaluations have shown that the display system is effective in generating direct P_s contours from level acceleration flight tests.*

Keywords: Specific excess power, LabView, level acceleration, flight test.

1 Introduction

Automated data acquisition and computation applications from flight test have been studied by various researchers in different ways using different approaches. This application performs all the calculations automatically in flight as a flight test is being performed. The work of the flight test engineer then becomes easy in contrast to the conventional way of manual data computation using excel spread sheet or different software's. Probably Hicks and Petersen's [1] study was the first to flight test and analyze display techniques for an aircraft. Their study exploited real-time measurement and display of in-flight flight performance parameters by a new simplified in-flight thrust computation method. In a study by Farhat [2], he and his research team conducted a test and evaluation of real-time predictive flutter analysis and continuous parameter identification of accelerating aircraft. A similar study by Young [3] automated the data reduction process for more efficient flight tests, and developed a Flight-Data Analysis and Reporting System (F-DARPS) in an attempt to decrease the time spent reducing data, by automating the entire data reduction process. In Atuahene et al.'s [4] study, they developed a real time energy management display which has the capability of displaying an aircrafts energy state and information, and attempted to achieve optimal flights in its evaluation.

This paper presents a study on the development and evaluation of a low-cost standalone display system for obtaining direct real time P_s contours from level flight acceleration flight tests. This information is useful in providing real time information on the aircraft's energy state, for aircraft performance analysis and for guidance in the event of attempts to change from one combination of speed and altitude to another as well as the flight technique to adopt during such maneuvers. We adapt some of the approach in our previous and ongoing study [4] and describe the current state of the display system as it is continuously being modified for improvement. The technique implemented uses the mathematical expressions that exist between velocity and altitude using kinetic and potential energies respectively. The "LabVIEW" software [10] is then used to program the algorithm to build the display system.

We have flight tested and evaluated the display using the UTSI's Aviation System's flight simulator with an X-30 hypersonic aerospace plane and a Piper Saratoga general aviation aircraft for both supersonic and subsonic flights respectively. From the flight simulation results, the display proved to be successful in obtaining direct P_s contours from level acceleration flight tests. The provision of guidance for flights along constant P_s contours was also feasible but only at low airspeeds.

2 Background

Research into automation of flight performance data reduction and computation in-flight has been explored in different aspects. The data reduction automation is one aspect and the display of results in a readily usable format for specific purposes is another. In the study in [1], they developed an application to monitor the interaction between the vehicle bending and torsion loads against load limit envelopes for critical airframe members. For this purpose, the dynamic characteristics of the structure were determined from real-time computation of the frequency and damping of five critical structural modes that were in turn graphically compared against predictions during the mission. The result was the development of a sophiscated real-time analysis and display which required careful integration of the aircrafts telemetry data downlink system and the NASA Western Aeronautical Test Range (WATR) mission control facility. This is obviously was a high end application in terms of cost and would be barely impossible for private and small aircraft industries to invest in. In [2], the researchers developed a simplified flutter analysis method that can be run real time to provide predictive frequency and damping values for maneuvers as flown using the aero-elastic problem that allows, among other things, partial pre-solutions and the usage of parallel processing. They also developed a technique based on an arbitrary Lagrangian/Eulerian formulation for stimulating accelerated flow problems and on window techniques. This application extracts frequency and damping values of an aircraft that is continuously accelerating. The study in [3] automated the data reduction process by developing algorithms programmed with the standard LabView math blocks and formula nodes for finding level, climb trim and phugoid through data flow. In [4], the study developed a real time energy management display which has the capability of displaying an aircrafts energy state and information, and attempted to achieve optimal flights in its evaluation.

Rutowski [5], Lush [6], Miele and Capillari [7], Sederstrom [8], Atuahene et al [4] and many others focused on investigating the practical benefits of energy management with [5] and [6] being the first to develop the methods of energy techniques. Sederstrom [6] was the first to apply the energy techniques in the development of an energy display. The methods presented above are high end applications in terms of cost, complex in nature, and would be barely impossible for private and small aircraft industries to invest in. This study presents a simple technique and off the shelf standalone display system for obtaining direct real-time P_s contours during a level flight acceleration flight test. It displays the plot of contours on a graph in-flight, thus using a data reduction method in the algorithm programmed into the LabView Software.

3 Methodology

Known values of P_s may be used to obtain the rate of climb and the acceleration capabilities of an airplane. The method developed by Rutowski [2] for solving aircraft's performance problems is based on the total energy of the airplane. The total energy of an airplane is the flight sum of its potential energy, as reflected by its altitude and its kinetic energy, and as shown by its airspeed or Mach number. There are two approaches used to derive the theory of climb performance [9]; Newton's approach based on Newton's second law, and the Energy approach which is sometimes called the Rutowski energy method [2] for Edward Rutowski who is credited for developing them.

3.1 Newton's approach

From Newton's second law, force is the product of mass and acceleration. This may be applied to an aircraft in climb. Assumptions are then made; that the angle of attack is small with the thrust line acting along the direction of flight, and that the aircraft is both climbing and accelerating in the direction of flight [9]. By computing the resultant forces in flight and making substitutions for flight parameters, we obtain the following equation;

$$\frac{P_{ex}}{W} = V_v = ROC = \frac{T_{av} - DV}{W} = \frac{P_{av} - P_{req}}{W} = \frac{dH}{dt} = P_s \qquad (1)$$

Where P_{ex} is the excess thrust power, P_{av} denotes the available power, T_{av} denotes the thrust available, dH/dt is the change in altitude with respect to time, V_v is the vertical velocity of the aircraft, W is the aircraft's weight, ROC is the rate of climb, D is the drag, V is the velocity and P_{req} is the thrust power required. The speed for best climb may then be determined as the velocity at which P_s is maximized (available power minus power required) for constant values of specific energy. From these equations, the curve from a plot of available power and power required essentially define the total performance of the aircraft.

3.2 Energy approach

This method is based on the principle of total energy. Total energy of an object is the sum of its Potential energy, (P.E) and Kinetic energy, (K.E). Similarly, making substitutions with forces in flight and flight parameters results in equation (2). The performance capability of an aircraft may be defined as the ability to change energy states with respect to time. This is obtained by differentiating specific energy, E_s with respect to time as in equation (2).

$$P_s = \frac{dE_s}{dt} = \frac{dH}{dt} + \frac{V}{g}\left(\frac{dV}{dt}\right) = \frac{(T - D)V}{W} \qquad (2)$$

Where, dV/dt is the change in speed with respect to time and g is gravity. At constant values of specific energy, we obtain a maximum altitude when the airspeed is equal to zero 'no acceleration' (this means kinetic energy is given in exchange for potential energy) [9]. On the other hand, the airspeed would be maximized when the altitude is equal to zero. This means potential energy is given in exchange for kinetic energy. E_s also known as energy height may be defined as the maximum speed an aircraft could achieve if all of its potential energy were converted to Kinetic energy or the altitude a flight vehicle would reach if all of its energy were converted into potential energy.

3.3 Real time specific excess power contours

Using equation (2), P_s is directly proportional to excess thrust (T-D) and velocity, and inversely proportional to weight. The expression for drag (equation (3)) may then be substituted into the relation and the equation simplified to obtain equation (4).

$$D = \tfrac{1}{2}\rho V^2 S C_D \quad (3)$$

$$P_S = \left(\frac{T - (\tfrac{1}{2}\rho V^2 S C_D)}{W} \right) V \quad (3)$$

Where C_D is the drag coefficient of, ρ is density and S is the wing reference area. Mach number and thrust values may be calculated using the analytical calculations presented in [4]. We then solve for P_s. The expression for P_s is then programmed with the algorithm as a function of the flight parameters and may be solved by an input of all the variables on the right hand side of the equation. On a flight test, the display may be connected to the aircraft's instrument panel which feed in these data for the computation. This is then displayed on either an altitude versus airspeed, P_s versus Mach or P_s versus velocity plot.

3.4 P_s display system

The Display system for obtaining direct real-time P_s contours was programmed with LabVIEW version 8.5 software and installed in the UTSI Aviation Systems engineering flight simulator for experimentation. Figure 1 shows the block diagram of the technique algorithm. Due to the large size of the block diagram, it has been resized to fit the representation. Figures 2 depict the display's intephase. During a flight test, only the plot desired may be selected to be displayed: (altitude versus airspeed, P_s versus Mach, P_s versus velocity, and velocity versus time).

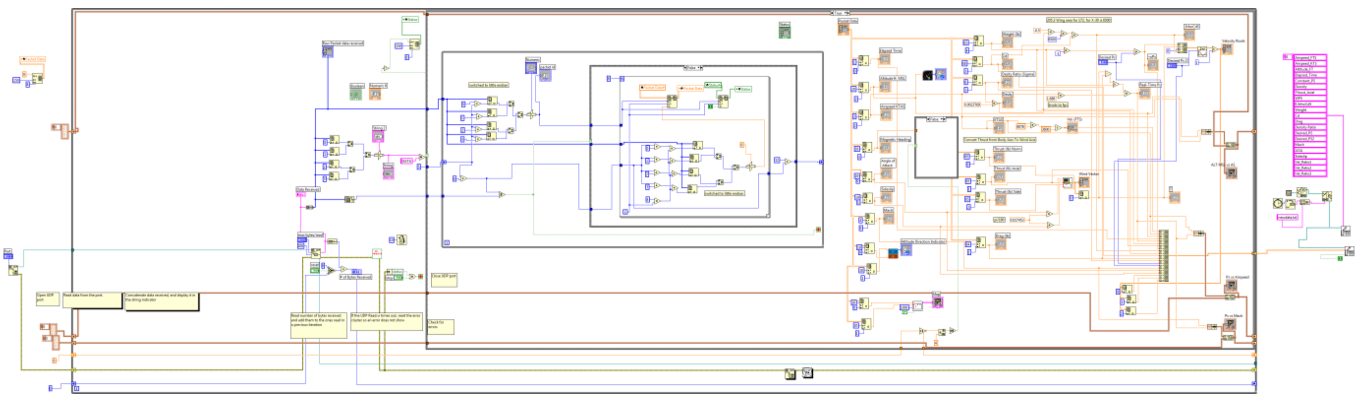

Figure 1. Block diagram for Standalone P_s Display System

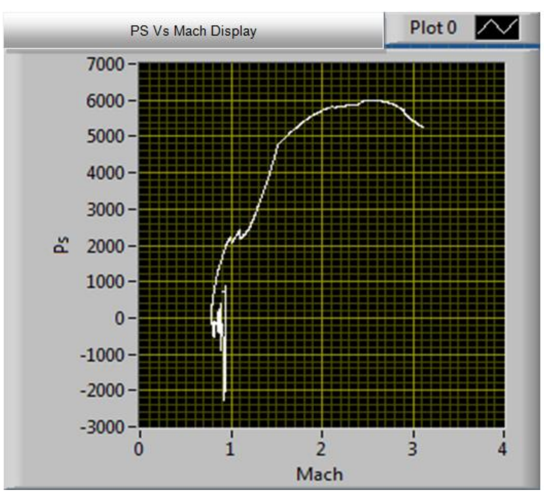

Figure 2. Standalone P_s Display System

4 Results and analysis

The Display system has been evaluated by generating direct P_s contours from level acceleration flight tests in the UTSI flight simulator and the results compared to that of an actual flight test conducted under the same conditions. P_s and velocity values computed from the conventional method in the flight simulator were inputted into the display under the same conditions of thrust, drag, weight and density to verify the accuracy of the technique's computation. Aircraft performance analyses in the form of P_s contours were generated with data from both Piper Saratoga aircraft and X-30 aircraft using the UTSI's engineering flight simulator. The purpose of this test was to compare the P_s contour directly generated from the present study with that generated by the conventional method and evaluate its accuracy and validity. The accuracy of the flight simulator's data was also checked for the evaluation.

The simulator flight test were performed by conducting level acceleration flight tests at different altitudes and the data recorded used to compute the specific excess power for both aircrafts. The Piper Saratoga was evaluated for altitudes ranging from 2000 ft to 10,000 ft, and airspeeds ranging from 180 ft/s to 350 ft/s. The X-30 aircraft was evaluated for altitudes ranging from 10,000 ft to 80,000ft and Mach 0.7 to 16.

The Piper Saratoga's P_s contours generated from the flight simulator were standardized and compared with data taken from an actual flight test at altitudes 4000 ft and 5000 ft. These were found to have slight variations. The comparison with an actual flight test helped to check the accuracy of the data from the flight simulator as well as the P_s contours calculated. At both altitudes, the actual flight test started at airspeed of 130 ft/s and reached a maximum level flight speed of 250 ft/s. At altitude of 4000 ft, the actual flight test had a maximum P_s of 12.3 ft/s at airspeed of 190 ft/s. At 5000 ft, the maximum P_s was 13.3 ft/s at airspeed of 230 ft/s. On the other hand, the flight simulator test started at airspeed of 180 ft/s and reached a maximum level flight speed of 350 ft/s. Also the flight simulator test had a maximum P_s of 15.9 ft/s and 14.2 ft/s at altitudes 4000 ft and 5000 ft respectively, and both occurred at airspeed of 275 ft/s. A variation of 3.6 ft/s and 0.9 ft/s P_s for the maximums was observed for altitudes 4000 ft and 5000 ft respectively. The variation in maximum level flight speed for both flights was 100 ft/s. The variations of the data from the flight simulator when compared with the actual flight test were considered acceptable. Data output from the flight simulator was linked to the display to provide real-time data (density, thrust, weight, and drag) for the computation.

Figures 3 and 4 depict the plots for the Piper Saratoga and the X-30 respectively. The cause of the irregularities and scattered points below the curves are due to elevator inputs to maintain level flight. This let to a resultant disturbance of the flight path and hence the real-time P_s computed. The test revealed that when the airplane is pitched down, thrust starts reducing; hence the P_s computed starts decreasing through zero to negative values. The display returns to the normal P_s values once the aircraft is leveled. The direct P_s may be plotted versus the airspeed or Mach number, or altitude versus airspeed/Mach from the data file output. The direct P_s values representing the different altitudes and airspeeds or Mach numbers may then be selected by drawing horizontal lines through each P_s on the vertical axis and selecting the P_s corresponding to each altitude and their respective airspeeds or Mach numbers. An altitude versus velocity/Mach number plot is then generated which is a representative of the P_s contours generated by the conventional method. The use of the display to generate direct P_s has been successful in achieving this.

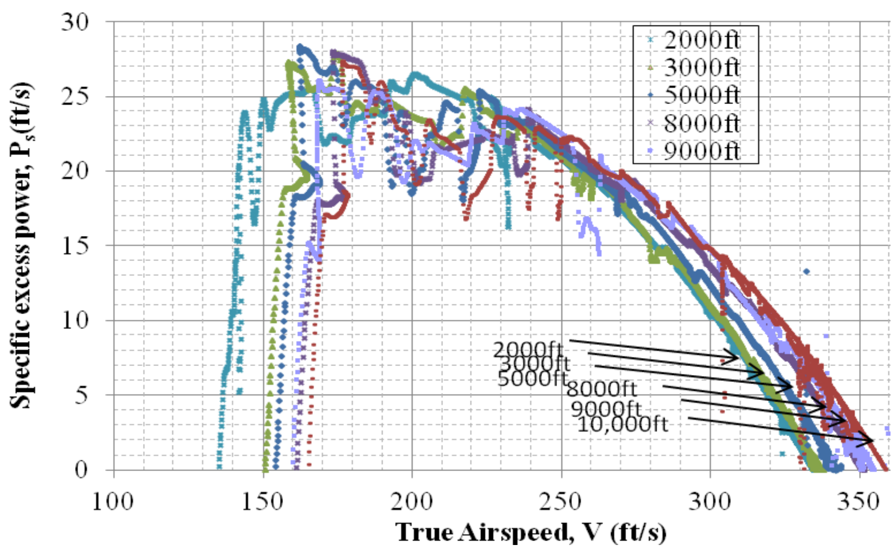

Figure 3. Specific Excess Power, P_s(ft/s) versus True Airspeed, V (ft/s) (Direct P_s calculated by display)
(Aircraft: Piper Saratoga Engine: Lycoming 300hp; Configuration: Clean configuration(Max power) ; Weight : 3600(lbs) ; Flight Conditions: hpo ~ 2000-10,000 ft, Vo ~ 150-355ft/s. ; Method: Level Acceleration)

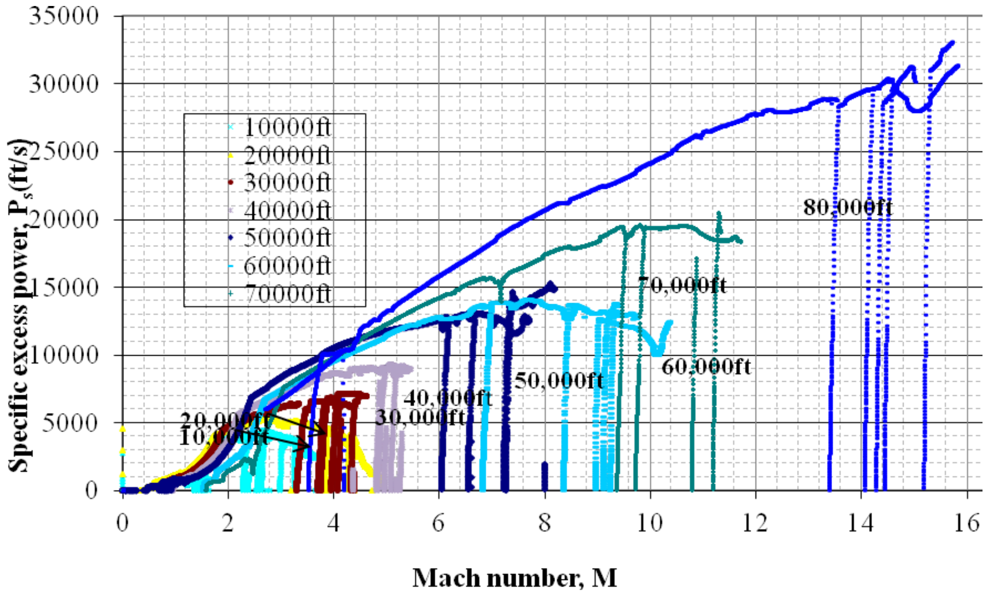

Figure 4. Specific Excess Power, P_s (ft/s) versus Mach number, M for X-30 aircraft. (Direct P_s calculated by display) (Aircraft: X-30, Engine: Rocket Engine; Configuration: Clean configuration (Max power); Weight: 550,000(lbs); Flight Conditions: hpo ~ 10,000-80,000ft, Mach~ 0.7-16; Method: Level acceleration)

5 Conclusions

A low-cost stand alone display system for obtaining direct and real-time specific excess power contours from level flight acceleration flight test has been implemented and flight tested in the UTSI Aviation Systems flight simulator, with a Piper Saratoga general aviation aircraft and an X-30 hypersonic aerospace plane. The utility of the display has been evaluated for generating direct P_s contours from level performance flight test and may be used on any aircraft. The technique algorithm relies on the input of the correct initial conditions and parameters specific to the aircraft being used. Flight test results have verified the accuracy of the P_s values computed. Such a standalone display system could provide technical and aircraft performance details while in-flight and lead to affective decision making in a test set up. Depending on the results obtained, the flight test engineer could decide whether the test should be run again to ensure quality conclusions on test results. The display could also serve as substitute or validation for the tedious and manual time consuming data reduction and computation used in generating P_s contours after a level acceleration flight test. Flight test engineers can easily and readily obtain direct P_s at any altitude during a level acceleration flight.

The display how ever has a few limitations. Since thrust and drag models are not available in actual flight tests, future studies would be devoted to perform some modifications to the display's algorithms thrust model. These parameters were interpolated from standard graphs and used in this study, which is accurate. But, actual thrust and drag models could be developed to get real time thrust and drag inputs to the display. The display is a useful research tool and would be useful in flight training and instruction in aircraft performance programs and flight testing schemes.

Acknowledgment

The authors would like to thank Dr Stephen Corda, Dr. Borja Martos, Michael Kamp and the Aviation Systems department of the University of Tennessee Space Institute for their technical support and instruction as well as the provision of the "Piper Saratoga" aircraft and the research flight simulator for flight test during the research process.

References

[1] Hicks, J. W. and Petersen, K. L., "Real-Time Flight Test Analysis and Display Techniques for the X-29A Aircraft", NASA Technical Memorandum 101692, 1988.

[2] Farhat, C., "(T&E) Real Time Predictive Flutter Analysis and Continuous Parameter Identification of Accelerating Aircraft", AFRL-SR-BL-TR-99-0106, Grant F49620-98-1-0112, 1999.

[3] Young, J. K., "Automating the Data Reduction Process for More Efficient Flight Tests and Reducing the Time from Days to Hours", Master's Thesis, University of Tennessee, 2010.http://trace.tennessee.edu/utk_gradthes/846

[4] Atuahene, I., Corda S. and Sawhney, R., "Development and Flight Test of A Real-Time Energy Management system", Taylor & Francis Group, Journal of Aviation, Vol. 15(4): 83-91, 2011.

[5] Rutowski, E., "Energy Approach to General Aircraft Maneuverability Problems," Douglas Aircraft Company Inc., March 1954.

[6] Lush, K. J., "A Review of the Problem of Choosing a Climb Technique with Proposals For a New Climb Technique For High-Performance Aircraft," ARC Technical Report, Memoranda No. 2557, June 30, 1948.

[7] Miele, A. and Capillari Jr., J. O., "Approximate Solutions To Optimum Climbing Trajectory For A Rocket-Powered Aircraft," NASA TN D-150, September 1959.

[8] Sederstorm, D. C., McLane R. C. and Branch, W. M., "Energy Management Display," 4th National SFTE Symposium, August 1973.

[9] Kimberlin, R. D., "Flight Test of Fixed-Wing Aircraft". Tennessee: University of Tennessee. ISBN-10: 1563475642, 2003.

[10] Johnson, G. W., and Jennings, R., "LabVIEW Graphical Programming," 4th Edition, Version 8.5, 2006.